MHD activity in high beta discharges in ASDEX Upgrade

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Introduction

The search for a steady-state tokamak solution has been the subject of intensive research during the last two decades on different tokamaks. The improved H-mode with high pressure is one of the main candidates for such a scenario. In this case, the normalized pressure, β_N, must be maximized and pressure driven instabilities limit the plasma performance. ($\beta_N = \beta\left(aB_t/I_p\right), \beta = 2\mu_0\langle p\rangle/B_t^2;$ $\langle p\rangle$ is the volume average pressure, B_t is the vacuum toroidal magnetic field at the axis, a is the minor radius and I_p is the plasma current.) These instabilities could have either resistive (mainly (m=2,n=1) and (m=3,n=2) Neoclassical Tearing Modes (NTMs)), or ideal character (n=1 ideal kink modes). In ASDEX Upgrade (AUG), the first limit for maximum achievable β_N is set by NTMs. Application of pre-emptive electron cyclotron current drive (ECCD) at the q=2 and q=1.5 resonant surfaces reduces this problem, such that higher values of β_N can be reached. In this regime, the plasma is marginally stable with respect to n=1 ideal modes. Two representative discharges from ASDEX Upgrade tokamak are shown in figure 1. The plasma stability is probed in the first discharge (#32156) by an externally applied magnetic field (figures 1a-1f). This magnetic field is produced by internal saddle coils (B-coils[1]) with n=1 main toroidal harmonic. These saddle coils have two toroidal rows of eight coils each and are located above and below the mid-plane close to the plasma. The NBI heating and ECCD are kept constant during the flattop. The plasma stability with respect to (2,1) NTM is lost around t=4 second and the mode grows. This leads to strong reduction of β_N (figure 1c). The mode reduces the plasma rotation (figure 1f) and the mode goes into a locking/unlocking regime depending on the B-coil current amplitude. Thus, the NTM stability has to be ensured to go to higher β_N.

Preemptive ECCD can help in this situation and the plasma beta can be increased further as shown in the second discharge (#32456; figures 1g-1n) for which a steady increase of beta with NBI power was preprogrammed together with NTM control. There, the limit is set by an ideal (2,1) kink mode, which later converts into an island (figures 1k and 1n) as discussed in reference [2]. More details about this type of scenario can be found in Ref [3].

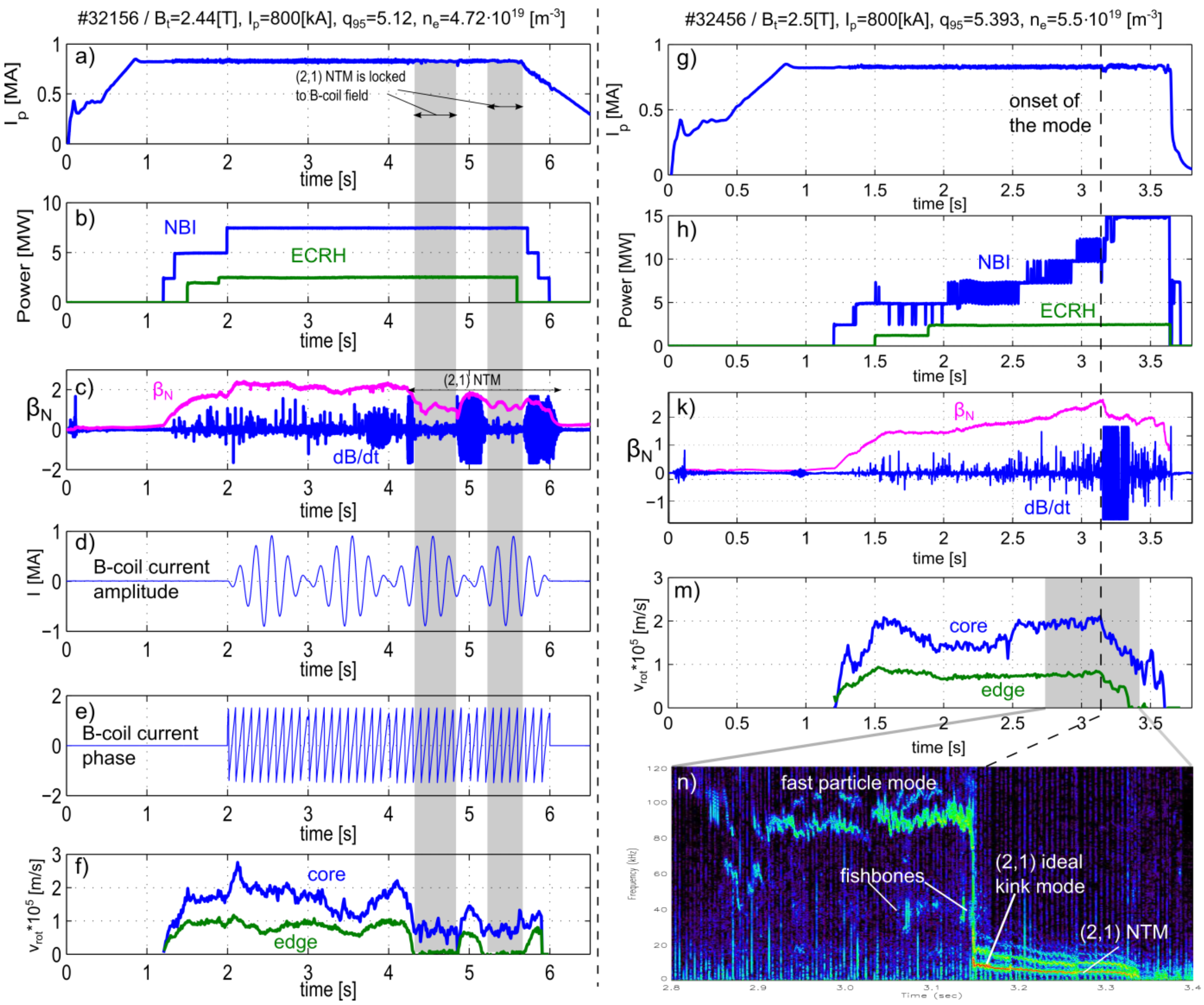

Figure 1. Two representative ASDEX Upgrade discharges are shown. Discharge 32156: (a) plasma current; (b) NBI and ECRH power; (c) normalized beta and magnetic coil signal; (d) B-coil current amplitude; (e) phase between upper and lower coils; (f) plasma rotation; The shaded time windows represent the locking phase of the (2,1) NTM to the B-coils (the same case is shown in figure 7 and discussed in section 4). Discharge 32456: (g) plasma current; (h) NBI and ECRH power; (k) normalized beta and magnetic coil signal, $\frac{dB}{dt}$; (m) plasma rotation; (n) spectrogram of the magnetic signal for the shaded time window.

Stability of discharges with respect to ideal and resistive modes

The appearance of an ideal instability in high pressure plasmas is a good indication of the proximity to a beta limit, in particular to the "no wall" limit. The exact value of β_N for this limit depends on many different factors: stabilizing influence of the conducting components facing the plasma surface, existence of external actuators (external n=1 perturbation, current drive, energetic particles) and kinetic interaction between the plasma and the marginally stable ideal modes. If these actuators are similar, details of the safety factor profile play an important role. Figure 2 shows two cases with slightly different safety factor profiles but the same value of β_N reached in experiments. Linear MHD calculations (CAS3D) show that the case in which the limit is set by an ideal kink mode (#33597) has a lower value of the "no-wall" limit ($\beta_{N,no-wall} = 2.97$) compared to the case with an identical value of β_N and small tearing modes (#32305, $\beta_{N,no-wall} = 3.3$). This is an expected result as discussed in reference [4].

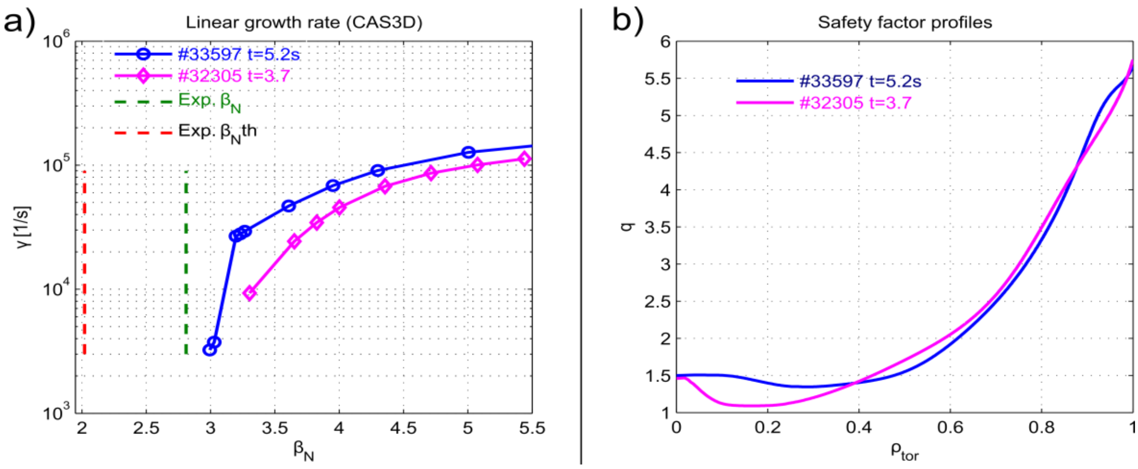

Figure 2. Stability analysis of AUG discharges with the same experimental β_N (including fast particles) and thermal $\beta_N th$ (without NBI particles): a) linear growth rates and experimentally achieved values for β_N and $\beta_N th$; b) corresponding safety factor profiles.

Different types of ideal mode behavior

There are two types of ideal mode behavior observed in high beta plasmas in AUG:

1) The mode has high rotation frequency ($3kHz - 20kHz$) and saturated amplitude for a sufficiently long time (hundreds of milliseconds). A typical example of such behavior is shown in figure 1n. This mode converts to an NTM at a later time point. Similar behavior was also observed in JET [5].

2) The mode grows fast and locks to the wall or external perturbations.

The best strategy presently is to avoid the mode onset since there is no good recovery algorithm for plasma confinement in this case.

Effect of the error field correction

As the normalized beta approaches the "no wall" limit, the plasma becomes less stable with respect to kink modes. In this situation, small external perturbations and error fields are amplified and influence the plasma behavior [6,7]. Recent experiments on error field correction show that correction with externally applied n=1 field delays the onset of the MHD modes. In a set of identical discharges, the poloidal beta was increased linearly by feedback control. The mode onset time is delayed for optimal error field correction settings ($I_{coil} = 200A, \varphi_{diff} = 90°, \varphi_{tor} = 0°..-25°$). As a result, a slightly higher β_N is achieved before the mode onset. Further optimization, in particular of error field correction and ECCD deposition position, will be necessary for stable operations at higher β_N.

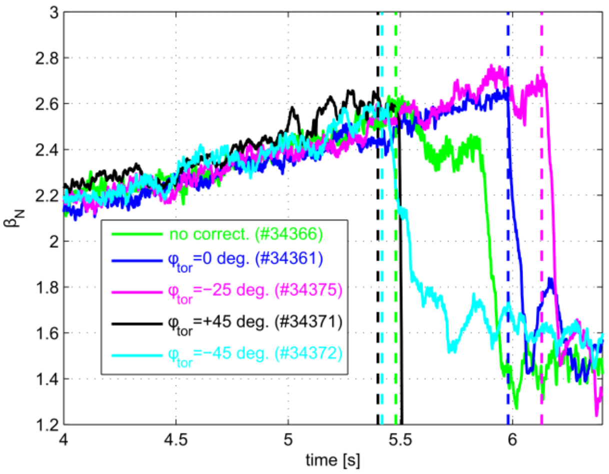

Figure 3. Evolution of the β_N without feedback and with feedback is shown. Onset of the n=1 mode is indicated by vertical dashed lines.

Acknowledgment

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